Fermi National Accelerator Laboratory
Technical Division
Development and Test Department
Mail Stop 316
P.O. Box 500
Batavia, Illinois • 60510

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Test of Insulation Electrical Strength of LARP Technological Quadrupoles (TQ)

D. Tooke, G. Ambrosio, N. Andreev, R. Bossert

Technical Division
Fermi National Accelerator Laboratory
Batavia, IL 60510

Abstract

This is a report about measuring the Insulation Electrical Strength of a TQC and a TQS practice coil. Tests were performed under transverse pressure up to 190 MPa at voltage up to 1000 V. Turn-to-turn insulation strength was measured between cables within the inner layer and within the outer layer. Layer-to-layer insulation strength was measured as well.

Introduction

The goal of the experiment is to test the electrical strength of the insulation between turns of TQS01 and TQC01 practice coils. These include turns within the inner layer, and the outer layer. It also includes testing the insulation strength between adjacent cables of the inner and outer layers.

In order to perform this test, a few items were mandatory. These items include a fixture to hold the coil, a high-pressure pump, and a power supply. The yellow press in IB3 was sufficient to apply the pressure to the coil sample. There was also a high-pressure pump attached to it. Before taking the tests, there needed to be a few conversions to be able to use the readout on the pump. A table was made, table 1, to convert the coil MPa into Pump PSI. For this particular setup, two 2 in. pushers and another section of the practice coil were used to apply pressure onto the coil (Figure 1).

Table 1. Conversion Table - Coil MPa to Pump PSI

Pump PSI for Two 2 in. Pushers

Coil MPa	Coil PSI	Pump PSI
0	0	0
30	4350.9	1336.1
60	8701.8	2672.2
90	13052.7	4008.4
120	17403.6	5344.5
150	21754.5	6680.6
170	24655.1	7571.4
190	27555.7	8462.1

coil width	0.8445	in
pusher length	2	in
cylinder surface	11	in^2

Pump PSI = (2 * Coil PSI * pusher length * coil width)/(cylinder surface)

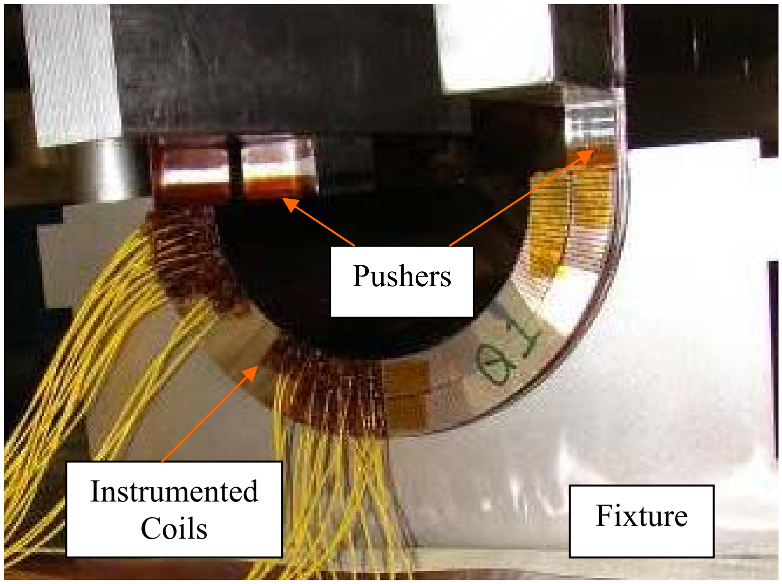

Figure 1. Sample inside the Fixture

Sample Description

The first measurements were taken from a TQS01 [1] practice coil. The TQ coil design is a quadrupole magnet consisting of a 2-layer cos-2θ configuration with a 90mm bore and one wedge in the inner layer [1, 2]. Cable and magnet parameters are presented in the following tables. The sample was an 11.5 in. long section of a TQS01 practice coil, including the return end and some straight section. The pressure was applied on the straight section through a 2 in. long pusher. Since the coil is much longer than the pusher, only the turns closest to the pusher were measured at the nominal pressure.
The second sample was a 3 in. straight section of a TQC01 [2] practice coil. This practice coil had been used for several mechanical models and other tests. There was a crack in the epoxy between the innermost turn of the inner layer and the pole (this crack developed during a cooldown into liquid nitrogen performed to cut the sample).

Table 2. Cable Parameters

Parameter	Unit	Value
N of strands	-	**27**
Strand diameter	mm	**0.700**
Bare width	mm	**10.050**
Bare inner edge thickness	mm	**1.172**
Bare outer edge thickness	mm	**1.348**
Cabling angle	deg.	**15.5**
Keystoning angle	deg.	**1.000**
Radial insulation thickness	mm	**0.125**
Azimuthal insulation thickness	mm	**0.125**
Copper to non-copper ratio	-	**0.89**

Table 3. Magnetic Parameters

Parameter	Unit	TQ2a
N of layers	-	**2**
N of turns	-	**136**
Coil area (Cu + nonCu)	cm^2	**29.33**
J_c(12 T, 4.2 K) = 2400 A/mm^2		
4.2 K temperature		
Quench gradient	T/m	**223.49**
Quench current	kA	**13.47**
Peak field in the coil at quench	T	**11.59**
Inductance at quench	mH/m	**2.278**
Stored energy at quench	kJ/m	**206.66**
1.9 K temperature		
Quench gradient	T/m	**240.57**
Quench current	kA	**14.57**
Peak field in the coil at quench	T	**12.48**
Inductance at quench	mH/m	**2.264**
Stored energy at quench	kJ/m	**240.31**

Figure 2. Sample TQ Practice Coil

Sample Preparation and Instrumentation

Voltage leads were soldered to every cable on the coil. A preferred method of use is to attach voltage leads to every other visible cable on both sides. This is to allow room for soldering. Next, all visible cables including the current leads were covered with insulating varnish. The varnish was used as insulation, and to help keep humidity off of the unprotected cables. It was also used to protect the leads from breaking off during high-pressure testing. After soldering the leads, the coil was then placed in a fixture to allow pressure to be spread over it in a high-pressure press (Figure 3). A Hi-Potter was used to apply voltage to the sample.

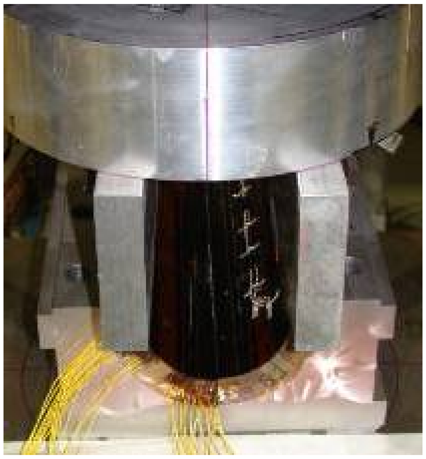

Figure 3. Coil in Fixture Ready for Testing

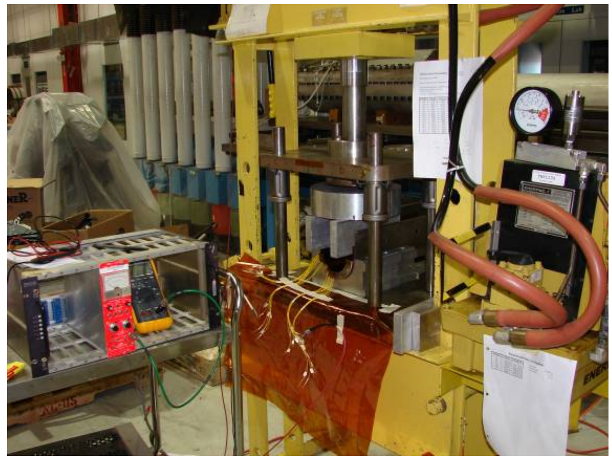

Figure 4. Complete Test Station

Measurement Procedure

The measurements were taken using a high potential tester, also known as a hi-potter. A multimeter was connected to the hi-potter to obtain a digital reading of the current passing between the adjacent cables under test (Figure 5).

Figure 5. Hi-Potter with multimeter

There were 3 series of tests performed on the first sample. The first series of testing involved checking for current leakage with no pressure applied on the coil. These measurements were performed at 100V, 200V, and 500V. Since there was no leakage detected, pressure was applied at 30MPa with the same three induced voltages. Again there was no leakage detected. This process was performed at 60MPa, 90MPa, and 120MPa. These steps were repeated until all of the insulation between adjacent cables of the entire sample was tested.

The second series of testing were performed at the same pressures as the first series of tests. The only difference is now the insulation was tested at higher voltage values. This time the current leakage was tested at 800V, 900V, and 1000V. Again all of the insulation between adjacent cables was tested. Since no current leakage was detected, a third series of tested was implemented.

In the third series of testing, the experiment was performed at even higher pressures. The first pressure tested was 150MPa. These involved measuring leakage at 100V, 200V, 500V, 800V, 900V, and 100V. Next, the pressure was increased to 170MPa at the same voltages. Fortunately, no leakage was measured as well. Again, all of the insulation between adjacent cables was tested. Later it was decided to apply an even higher pressure. The pump used for this experiment was labeled to begin overloading at 9000PSI. Due to this factor, the highest pressure tested was 190MPa (Table 1). In order to keep the pump from overheating, fewer measurements were performed. Insulation was tested between turns 1-2, 2-3, and 3-4 within the outer coil and inner coil. For testing insulation between the outer and inner coil, testing only occurred for leakage between inner turn 1 and outer turn 1, inner turn 2 and outer turn 2, and finally inner turn 5 and outer turn 6.

Test on the outer layer of the second sample showed in some turns high current leakage at no pressure and low voltages. The insulation between these turns has very likely been damaged during the use of the practice coil for mechanical models. Therefore it was decided to use only the inner layer turns for this test.

1st sample (TQS-practice coil) results

Upon measuring the current leakage from 0MPa to 190MPa at 100V to 1000V, there was no leakage detected. The sensitivity of the analog amper-meter is .004μA. Only the first turn-pair (closest to the pusher) of the outer layer showed current leakage of about .004μA at pressure equal to and higher than 120 MPa, and voltage equal to and higher than 800 V. A digital multimeter used at 120 to 190 MPa didn't show any detectable current.

2nd sample (TQC-practice coil) results

Test of the inner layer of the TQC01 practice coil gave the results shown in Table 4. The sample had 36 turns on the inner layer (18 per side). The electrical strength was measured between all adjacent turns and between the two innermost turns around the pole. Table 4 shows the turn-pairs where some current leakage was measured or trips (voltage breakdowns) occurred. All other turn-pairs didn't show any detectable leakage up to 190 MPa and 1000 V. Turn 18 was on a side of the pole where there was a crack in the epoxy (developed during a cooldown at liquid nitrogen performed to cut the sample). The trips between turns 17-18 and turns 16-17 are likely caused by this crack. The same thermal shock may have caused a crack in the epoxy between the pole and turn 19 (on the other side of the pole). The trips between turns 32-33 and 34-35 occurred at sufficiently high voltage. The voltage at which the insulation tripped decreased with increasing pressure (therefore Table 4 shows the minimum voltage at which trips occurred for each turn-pair). At 0 MPa, trips were only located at the insulation between turns 17-18 and 34-35. At 120 MPa, new trips occurred between turns 16-17, 18-19, and 32-33.

Table 4. TQC practice coil results

Insulation Between Turns in the TQC Inner Coil						
Turns	Pressure = 190 MPa					
	100V	200V	500V	800V	900V	1000V
I5 - I6						0.004μA
I6 - I7						0.004μA
I8 - I9						0.004μA
I16 - I17			trip			
I17 - I18			trip			
I18 - I19	trip					
I32 - I33					trip 860 V	
I34 - I35				trip 745 V		

Note: The yellow line shows the turn-pair separated by the pole.
For turn pairs I32-I33 and I34-I35 the table shows the actual voltage at which the trip occurred.
No current leakage was detected between any other couple of turns at any pressure (up to 190 MPa) and voltage (up to 1 kV)

Conclusions

Measurements of the electrical strength of samples cut from TQ practice coils have shown that the TQ turn-to-turn insulation can withstand high voltages (more than 600 V) under transverse pressure up to 190 MPa. At 190 MPa a turn-pair had a voltage breakdown at 745 V, and another turn-pair at 860 V. Both turn-pairs were parts of a practice coil that had previously been intensely used in TQ mechanical models.

References

[1] S. Caspi, et al.,*"Design and Analysis of TQS01, a 90 mm Nb_3Sn Model Quadrupole for LHC Luminosity Upgrade Based on a Key and Bladder Assembly"*, IEEE Transactions on Applied Superconductivity, vol. 16, no. 2, pp. 358 - 361, June 2006

[2] R.C. Bossert, et al.,*"Development of TQC01, a 90 mm NB_3Sn Model Quadrupole for LHC Upgrade Based on SS Collar"*, IEEE Transactions on Applied Superconductivity, vol. 16, no. 2, pp. 370 - 373, June 2006